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## INVESTIGATION OF DAILY NATURAL AND RAPID HUMAN EFFECTS ON THE AIR TEMPERATURE OF THE HAJNÓCZY CAVE IN BÜKK MOUNTAINS

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### Abstract

The aim of this study the authors measured and analyzed the effect of the exterior daily temperature change on the interior temperature in a dripstone cave visited by cavers exclusively. The measurement was carried out in the Hajnóczy Cave located in the southern part of Bükk Mountains in Hungary. Although only one entrance is known, there are more evidences for the strong effect of exterior conditions on the interior processes like temperature fluctuation and dripstone development. Using high resolution wireless digital thermometer sensor network the air temperature and air humidity were measured in 32 points in every 10 minutes for long time but now the data of a 8-days period were analyzed. Based on these data different zones of the cave could be separated and during summer conditions the climatic variability of the entrance transitional and deep cave zone was described. Based on statistical analysis of spatial information significant correlation was found between the exterior temperature fluctuation and that of such a cave chamber, which is relatively far from the cave entrance. This fact proves that existence of a fissure system which is permeable for air but not passable for cavers. During the measurement the human effect was also analyzed and 0.3–0.6 °C temperature rising was recognized for a short time. Because of the surface vicinity the effects of the environmental change can have sensible impact on the cave and its natural phenomena. Among others temperature rising, air humidity decreasing were detected in present study.

**Keywords:** cave temperature, wireless sensor network, Hajnóczy Cave

### INTRODUCTION

The macroclimate is the determining factor for karst development and formation of surface and subsurface processes. Beside the general macro scale processes, however the microclimate factors have important effects on ecological mechanism and other natural processes like corrosion, erosion, dissolution. Generally it can be stated, that the microclimate has an impact on cave morphology, biology (flora and fauna), and management. The scientific research started mainly in mid 20<sup>th</sup> century with the investigation climate of caves and its influence upon cave organisms (Poulson and White, 1969). Jakucs (1977) investigated the connection between microclimate factors and chemical processes in soil and limestone layer. de Freitas and Littlejohn (1987) analysed the impact of cave microclimate upon sensitive cave fauna and cave management. The 3-zone model has been developed to describe the general zones of climatic variability within a cave (Copley, 1965; Poulson and White, 1969; Fodor, 1981). According to this 3-zone model, a twilight zone exists near the cave entrance with greatest variability in microclimate parameters. Moving from the entrance towards the interior of the cave, the influence of exterior climatic conditions diminishes and a middle zone exists in complete darkness with some variability in cave microclimate. Further in the

cave, at the rear, a deep cave zone exists with constant microclimatic conditions (Gamble et al., 2000).

The great improvement achieved in the last decades are mainly due to the new technology and particularly to the inexpensive data loggers which record unattended a great number of data. At the same time, the financial support of some show caves to carry on environmental researches and to evaluate the visitors' capacity was instrumental in the development of cave climatology (Hoyos et al., 1998; De Freitas et al., 2006; Lario and Soler, 2005). The high resolution microclimate study can give very useful spatial information about the air mass movement not only in the show caves but in such caves which are used and investigated only by researchers (Cigna, 2002). New entrances, new interior passages can be found according to the analysis of detailed spatial information based on microclimate measurement.

### STUDY AREA

The Hajnóczy Cave is located on the South-Western part in Bükk Mountains (*Fig. 1*). The cave was formed in Middle Triassic Ladinian and Upper Triassic Karnian cherty grey limestone. The cave entrance can be found on the Odorvár hill slope at 475 m above the sea level.

Odorvár (574 m) is a limestone hill situated in the western side of the valley of the Hór creek. The “odor” word means area with hollows. The total length of its corridors is cca. 4257 m, the vertical difference between the highest and deepest points is 125 m (Fig 2.).



Fig. 1 Bükk Mountains (Mucsi L.)

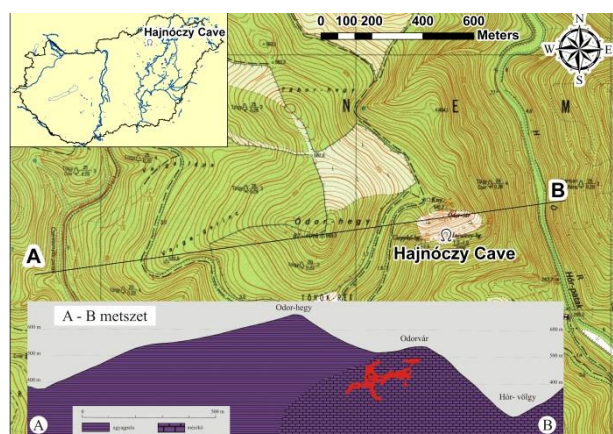


Fig. 2 Hajnóczy Cave location on topographical map (Muladi B.)

The air temperature measurement was carried out in the two morphologically distinguishable parts of the cave (Varga, 2003).

The first investigated area was the entrance part of the cave, which can be characterized by narrow corridors. After this part the cave halls were formed along bedding planes by karstic corrosion. This kind of passage system, which is rich in narrow corridors, continues from the cave entrance through The House-top (Háztető) and Ruin hall (Rom-terem) to the Great hall (Nagyterem). This part can be described as a labyrinth, in which the distance between the bottom and ceiling of the halls is continuously increasing.

Further part of the cave can rather be described as part of large halls formed by erosional processes and by small corridors which connect these halls. This part contains the Leyla, and the very narrow passage Almond (Mandula) called after its cross section shape. After the Almond passage the Gallery of 10-15 m high hall follows. This is one of the most beautiful halls of the cave because of the uncountable stalagmites. The largest hall of the cave called as The Giant hall is the last hall on this west-eastern part of the cave. The horizontal dimension

of this hall is 62\*16 m, while the vertical dimension is 10-12 m. The ceiling of the Giant hall is very near to the surface as shown by the tree roots that can be seen on the walls. The western part of the cave can be found in limestone layers which are covered by older dark grey shale.

The Hajnóczy Cave was discovered in 1971, and the mapping and the scientific investigation started immediately after its discovery. The first air temperature measurement campaign was executed by Miklós, G. and Városi, J. from 1975 to 1977. According to their measurements the air temperature ranged from 8.5 °C to 10.5 °C. The relative humidity was higher than 98% on average, but there were wetter and drier halls in the cave. Up to now is observable the fact that the halls near to the surface are drier, while the halls and corridors deep under the surface are more wet.

If the difference between the cave and surface air temperature is about 10 °C, then the amount of the moving air is cca. 0.4 m<sup>3</sup>/s. The velocity of the air ranges from 5 to 25 cm/s, and at the entrance part it was 20-40 cm/s, while the air flow impulsion reached 50 cm/s (Miklós, 1978).

## DATA AND METHODS

Present research activity started in December 2011. Almost 2 years of continuous measurements have resulted in detailed information about the annual trend of the cave air temperature and main features of cooling and warming processes (Muladi et al., 2012). Aim of our study was to determine the spatial profile of air temperature of the cave developed during summer air circulation period in July 2012. Horizontal air movement and vertical lamination could be identified because digital equipment was installed in the cave at the same time, in different halls and corridors. The air humidity was also measured beside the air temperature.



Fig. 3 UC Mote Mini (Muladi B.)

UC Mote Mini low power wireless sensor module developed at the University of Szeged was used for our measurements (Fig. 3). This device promotes IEEE 802.15.4/ZigBee wireless communication protocol in order to realize a low data rate. The radio module can operate at a data rate of 250Kbps in ISM 2.4Ghz band. The control is regulated by 16 MHz Atmel ATmega128RFA1 microprocessor with 128kB RAM. Several types of sensors are integrated into this device.

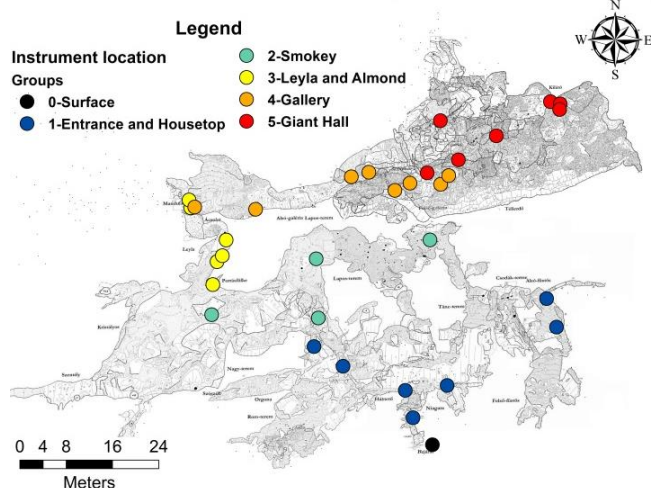


Fig. 4 Hajnóczy Cave map and devices location

The accuracy and the scale of SHT21 temperature and the humidity sensor are  $\pm 0.3$  °C,  $0.01$  °C and  $\pm 2.0\%$  RH,  $0.04$  % RH, respectively. Data collection can be realized with 2MB external flash TinyOS, which is a small open-source energy-efficient software operating system, supporting large scale self-configuring sensor networks. The device is powered by LIR2450 battery (Senirion, Datasheet SHT21). During our study, data were recorded in every 10 minutes. The sensors could be used for more than 3 months without battery replacement.

The data obtained every 10 minutes were evaluated using a matrix of correlation coefficients. First, data were averaged according to hour and day, resulting in a new dataset. Then these data were processed with pair wise correlation coefficients in order to investigate the direct and indirect relationships among cave airflows.

The temperature and relative humidity of cave air were detected using 32 sensors (14 of them can also measure air pressure) in Hajnóczy Cave. In each case one of the sensors was placed near the cave entrance to measure surface temperature (Fig. 4).

## RESULTS

According to the direction of the air movement the Hajnóczy Cave is rather a through cave than a big cave, apart from the fact that it has only one known entrance. One part of the main halls is situated in relatively higher position to the entrance and these halls are near to the radiated southern hill slope. So during summer meteorological conditions, when the exterior air mass is always warmer than the air in the cave, the cooler and heavier

air mass of the cave is continuously flowing out through the cave entrance. At the same time warmer exterior air moves to the cave through the fissure system in the limestone layers. In this case 3-4 °C difference can be measured in the air temperatures in different parts of the cave.

The minimum air temperature was 8.2 °C during the summer measuring period which is equal to the annual mean temperature of this hilly region. Because of the insulating effect of the buried limestone layer (in some places its thickness is less than 4-5 m) the maximum air temperature was higher than 11.2 °C. In 1975-77 the air temperature measurement was carried out by analogue instruments but the results can be compared to our data which were collected by digital thermometers. The air temperature ranged from 8.5 to 10.5 °C that time, which means that there is no significant difference between the data of these two datasets.

The 0.7 °C difference between the maximum values can be the reason for the higher monthly mean temperature on July 2012 (24.1 °C) compared to the lower monthly temperatures measured in 1975-77 (20.6-22 °C).

The results of the analysis of air mass movement and the effect of the exterior air to the air temperature of the cave is presented in this paper. The results are based on the data which were collected from 01<sup>st</sup> July to 09<sup>th</sup> July 2012.

### Surface, Entrance and Housetop, Smoky

One thermometer was installed near to the cave entrance to measure the temperature of the exterior air mass. During the measuring period the maximum values ranged between 33 and 35 °C, while the minimum values changed between 13 and 23 °C (Fig. 5b).

During the summer air circulation period the air mass is flowing out from the cave through the total section of the entrance. The passages near the entrance are sink-like, because the surface conditions have an effect on the air temperature just within the first few meters from the entrance. The influence of the convection is so intensive in this part of the cave, that the effect of a visiting group could not be measured. After the entrance part, where 3-4 smaller halls are located, the velocity of the air mass decreases, so vertical lamination of the air mass can be proved by the decreasing air temperature. The sensor located very near to the entrance measured 10.8-10.9 °C with slightly traceable daily fluctuations (No. E1 on Fig. 5b). The following sensor detected almost with 2 °C lower air temperature about 5 m from the entrance. The graph of this data also show daily fluctuation, but the difference between the minimum and maximum values is less than 0.1 °C. At the Housetop the air temperature was changed between 8.2 and 8.3 °C without any daily fluctuation (No. E3 on Fig. 5c).

The Lower and the Upper Smoky halls are located east to the Housetop in the labyrinth-like part of the cave near to entrance. They called after the black colour walls, which might be the results of the manganese content of the stalagmite coverage.



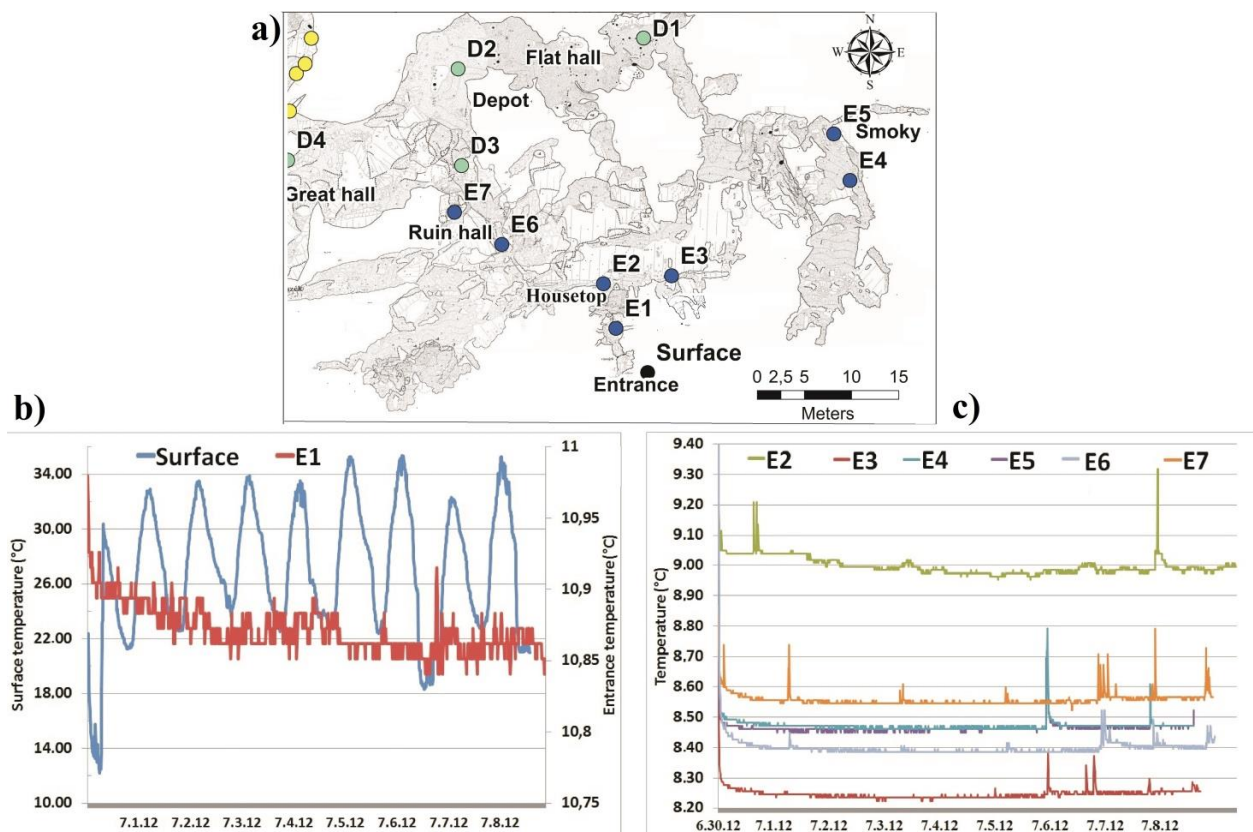


Fig. 5 Sensors location (a) Surface and entrance (b), Housetop, Smokey and Ruin hall (c) temperature data (°C)

The Upper Smokey hall is relatively dry because of its closeness to the surface. The Lower Smokey hall has a narrow connection to the Upper Smokey hall, and it is a “bag-like” place, where constant air temperature (8.4 °C) was measured (No. E4, E5 on Fig. 5c).

The Ruin hall is situated west to the Housetop-between entrance zone and Depot hall as transitional zone between them. Two sensors were installed in this hall (No. E6, E7 on Fig. 5a), and the air temperature ranged from 8.4 to 8.55 °C in the analysed period without any daily fluctuation. The sensors were located near to the cavers pathway so human heat radiation sometimes increased the air temperature with 0.1-0.2 °C (No. E6, E7 on Fig. 5c). The position of the Ruin hall is similar to the Lower Smokey hall; both are big-like room in which the air temperature does not change in a short period.

The Ruin chamber is connected with the Great chamber by the Depot. The Depot is the first room in which the cavers can deposit their measuring and research equipment onto a horizontal surface safely. From the Depot the pathways forks, one path leads to the Great chamber, the other one goes back to the Lower Smokey room through the Flat chamber.

The Depot steeply leads down from the Ruin chamber to the Great chamber. Few years ago the cavers climbed out a chimney-stack over it. This almost vertical passage was called White fox chamber.

During the summer measurement 2 sensors were deposited in Depot (No. D2, D3 Fig. 6a), one on the top and one on the bottom. A third sensor was

hanged in the middle part of the Flat chamber (No. D1 Fig. 6a). Cold air mass (8.3 °C) was in stable situation on the bottom without any daily fluctuation (see graph labelled D2 on Fig. 6b), while the warmer air temperature was measured on the top of this chamber (8.8 °C).

The Flat hall (Lapos-terem) is located further on the entrance but the temperature data of the sensor situated in this hall (D1 on Fig. 6b) show very strong influence of surface. The daily fluctuation of the air temperature is not so high ( $\Delta T = 0.12$  °C) but it was detectable by the sensor.

Peaks on the graphs are the effects of the visiting groups on air temperature. For a short period the air temperature was higher with 0.1 and 0.3 °C in the Lower Smokey hall after visits of 3 cavers on 6<sup>th</sup> and 8<sup>th</sup> July 2012 (Fig. 7). The Flat hall has smaller air volume because the average height of this hall is about 70 cm so the human effect on air temperature was more significant ( $\Delta T = 0.2-0.4$  °C) after the visiting of 4 persons on 7<sup>th</sup> July (Fig 7).

It was very surprising to observe clear daily temperature fluctuation during summer air circulation condition in the Flat hall which is located far from the cave's entrance. Miklós and Városi supposed that the air mass is moving from the Giant hall toward the entrance (Miklós, 1978). The distance between the Giant hall and the Flat hall is large and the air mass velocity in the cave is low consequently air convection from the Giant hall would not have an effect on the air temperature of the Flat hall. Subsequently, there has to be a connection between the surface and the Flat hall through an unknown entrance or through the fissure system and cave passages.

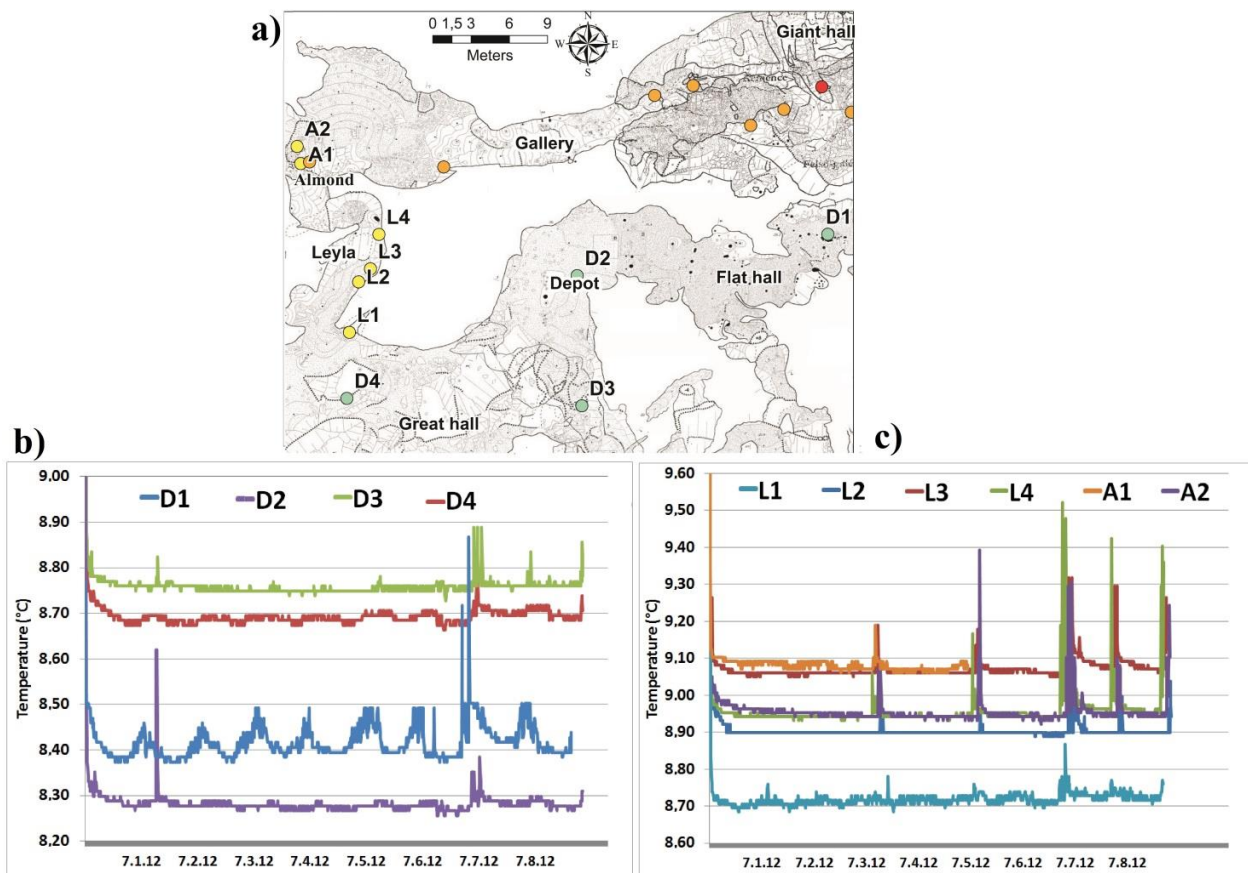


Fig. 6 Sensor location (a) Depot and Great Hall (b) and Leyla and Almond (c) temperature data (°C)

To prove our assumption first of all the correlation between the surface and Flat hall's temperature was calculated. Foremost the graphs were smoothed using following equation:

$$T_i = (\sum T_{i-j}) / 11 \quad j = -5, \dots, 5$$

where

$T_i$  = average temperature in a given time (i)

The daily maximum temperature value in the Flat hall was reached at a later time than the maximum value of surface temperature. This time-lag was fluctuating daily as a function of the difference between the daily maximum and minimum surface temperature. The min-

imum delay was 1.3 hour, and the maximum delay was 4.8 hour.

The correlation between for the daily temperature values of the Flat hall and surface was calculated using the sliding cross correlation method. The correlation coefficient ( $r$ ) expresses the strength of the relationship between the two variables.

$$r = \frac{\sum (x - M_x) \cdot (y - M_y)}{\sqrt{\sum (x - M_x)^2 \cdot \sum (y - M_y)^2}},$$

where

$M_x$  is the mean of the  $x$ , and  $M_y$  is the mean of the  $y$  variable.

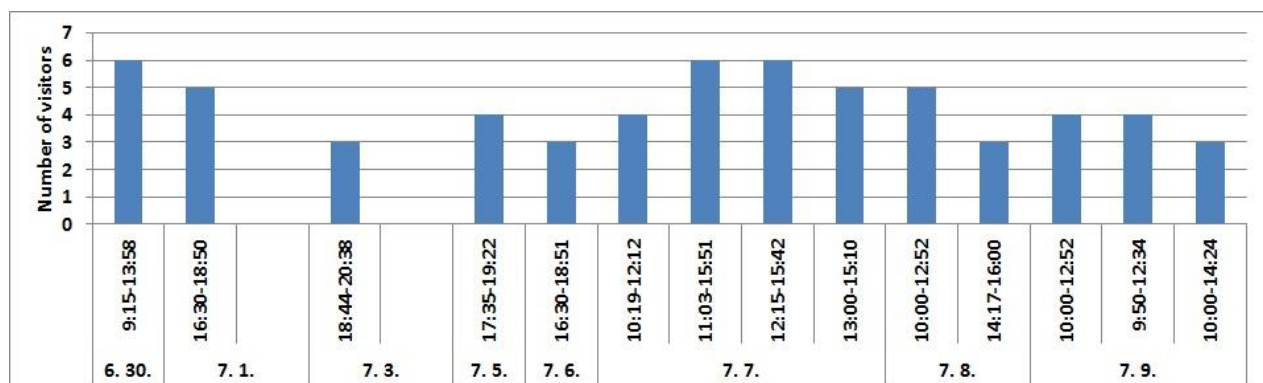


Fig. 7 Number of cavers in the cave (Source: Leader of the Hajnóczy József Speleological Research Group)

Table 1 The differences of the time and temperature

Date	1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul	8-Jul
Time difference based on sliding correlation	2.5	4.8	4.1	2.1	4.5	1.3	1.7	1.3
Daily surface temperature difference	11.3	10.6	10.2	9.8	12.1	15.9	13.4	14.4
Maximum sliding correlation	0.90	0.94	0.86	0.85	0.89	0.85	0.96	0.88

The correlation coefficient ( $r$ ) can be ranged between -1 and 1. If the value is close to -1 or one there is a strong connection between the values, if it is close to 0 the connection is random. A positive value indicates a positive connection, while a negative value indicates a negative relationship (Pécze, 1979).

The 8 day analysing period was divided into 8 segments considering the measured time-lags, and then the correlation coefficient was calculated for the daily values. According to the cross-correlation method, the maximum value of the daily correlation coefficient ranged between 0.85 and 0.96 (Table 1), consequently there is a significant connection between the daily temperature values of the Flat hall and that of the surface.

The highest correlation coefficient was shown at different time-lags in this period. Miklós and Városi stated 35 years ago that there can be strong connection between the highest outer air temperature value and the value of the cavern air velocity. According to our statistical analysis a strong opposite relationship exists between the difference of the maximum and minimum surface air temperature ( $\Delta T$ ) and the length of time-lags (LTL). The following function defines the numerical connection between time-lag (dependent variable) and  $\Delta T$ . (Fig. 8)

$$LTL = -0,4279 \Delta T + 8,0142$$

The correlation coefficient  $r$  is equal to -0.64, which shows negative correlation between these parameters.

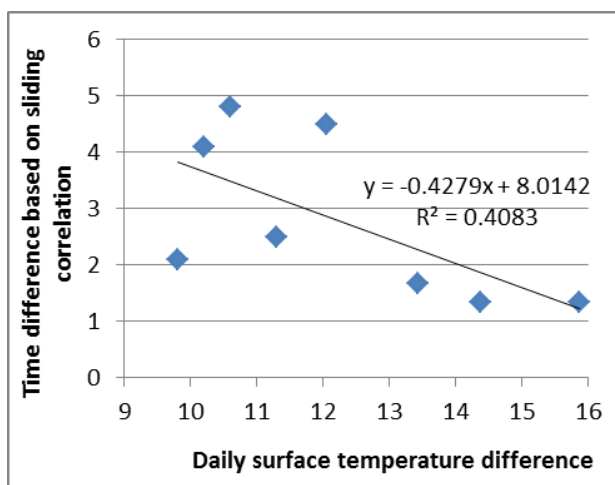


Fig. 8 Time difference based on sliding correlation and daily surface temperature difference

We proved that the air temperature is affected by the outer air mass in the Flat hall, which is located far from the entrance. If the air is moving out from the cave through the entrance there has to be one or more paths in which the outer air masses can reach into the cave. One of these paths might be the passages which connect the Upper Smokey hall with the Flat hall. The other more probable pathway is the White fox chamber, which is a vertical passage above the Depot hall. During the discovering of this chamber, the researchers found animal bones. These bones were washed into the cave many years ago, indicating that there has to be an open fissure system somewhere above the currently known entrance. The thickness of the limestone layers has to be less than 5-6 m. This value is based on the data of the cave map of high accuracy and digital elevation model calculated from stereo aerial imageries. The spatial distance between the supposed end of the fissure system on the surface and the sensor location is cca. 40-50 m, therefore the velocity of the passing air has to be cca. 0.5-1 cm/s if we calculate by the known time-lags (1.3-4.8 hours) (Fig. 9).

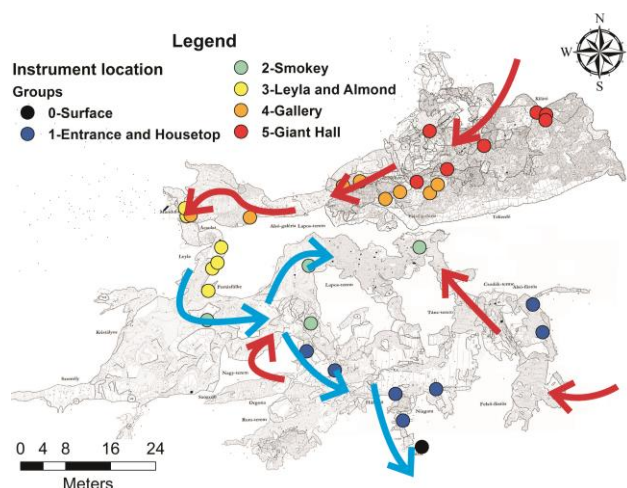


Fig 9 Hajnóczy Cave atmospheric circulation

The Great chamber is the largest chamber in the cave's first zone (48 m long, 14 m wide and 5-8 m high). There are few stalagmites in it and calcite crystals on the wall of a dried out pond (Fig. 10).

Daily fluctuation of air temperature can be seen on the graph belongs to the data measured in this chamber (No. D4 Fig. 6b), so we can take it that the exterior air can directly reach this chamber through the fissures above it.



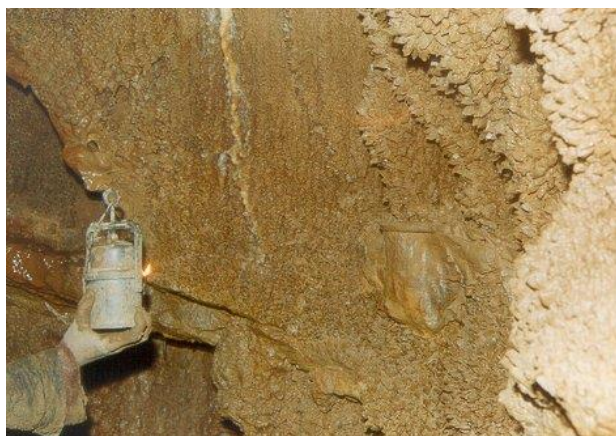


Fig. 10 Great chamber calcite crystals on the wall (Mucsi L.)

The Leyla and the Almond passage are found on the north eastern part of the Great chamber. This is the way to the main section of the cave, what contains the for example the Grand Canyon and the Tsitsogó on its western part and Gallery and Giant chamber on the eastern part of it. The Almond passage was closed by limestone and shale agglomerate for thousands years until 1977, when the cavers broke through that (Fig. 11).

The highest value of the velocity air convection can be measured in the Almond passage in the Hajnóczy Cave, because large volume of air mass has to move through on a tunnel whose cross section is less than  $0.25 \text{ m}^2$ .

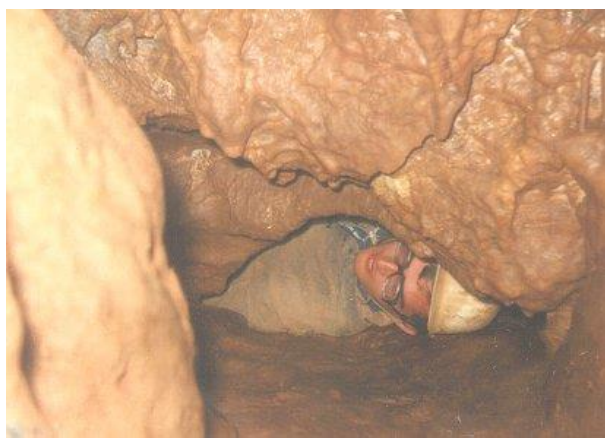


Fig 11 Almonds passage (Miklós G.)

Miklós and Városi measured 20-40 cm/s air velocity in Almond in 1977. The air is flowing from the Gallery toward the entrance in summer. The air temperature ranged between 8.7 and 9,1 °C in July 2012 with a fine daily fluctuation. Because of the tight cross section of the Almond passage the temperature increasing effect of the visitors (cavers) can be measured and the rate of temperature rising is 0.5-0.6 °C.

### Gallery

The Gallery is one of the most beautiful parts of the cave. Its dimensions are: 70 m long, 1-8 m wide and 4-13 m high (Fig. 12). The reason for the stalagmite formation is the vertical position of thin limestone layers. Large amount of infiltrating saturated karst water can get into the cave along the limestone layer and after the dropping from the ceiling to the bottom of the hall the stalagmites (columns) grow bigger. Miklós and Városi measured a little bit higher air temperature in the Gallery in 1975 than in the entrance part, but the position of the measuring equipment is unknown. Therefore 7 sensors were utilized in our measurement in 2012 and vertical lamination of the relatively calm air mass was detected (Fig. 13). The measured air temperature values are higher than that of the deeper parts of the cave, because upper part of this chamber is not so far from the eastern slopes of Odorvár.



Fig. 12 Gallery stalagmite formation (Mucsi L.)

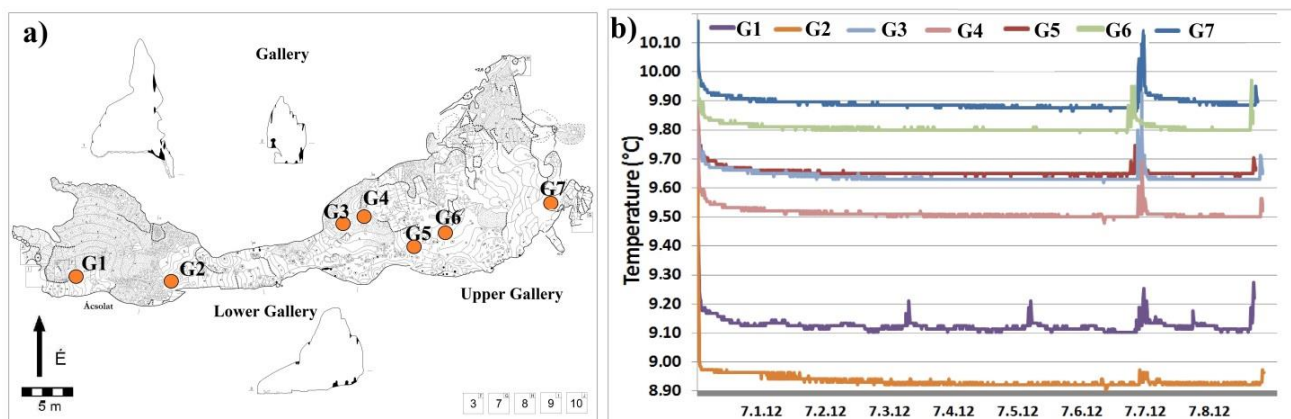


Fig. 13 Gallery's sensors location (a) and temperature data (b) (°C)

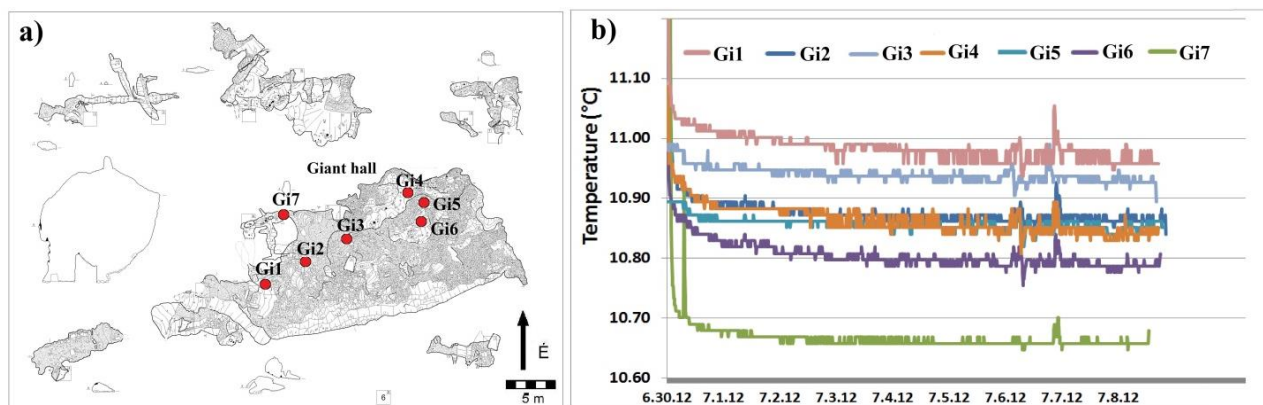


Fig. 14 Giant Hall's sensors location (a) and temperature data (b) (°C)

### Giant Hall

The entrance to the Giant chamber can be reached from the eastern end of Gallery through huge collapsed rock blocks. Almost whole skeleton of *Ursus deningeri* was found near to these blocks in the Upper Gallery under a 3-5 cm thick dripstone layer. This fact also proves the vicinity of the surface. The Giant chamber is the largest chamber of the Hajnóczy Cave (63 m long, 16 m wide and 14 m high).

The Giant chamber is the driest part of the cave because it has very small catchment area, and the air humidity is lower because of the relatively high air temperature (10.67-11 °C). This is the reason of the thin limestone layer. The tree roots can reach the ceiling of the Giants hall (Fig 14).

The reason of this is that there is a thin limestone layer above this cave chamber proved by the tree root hanging from the ceiling. About 4 m<sup>2</sup> area was covered with bat's guano in 1980's, when this chamber was discovered and few flying and hanging bat can be seen in this part of the cave which is also the evidence of the surface vicinity. Because of the low air humidity and few seeping water some of the formerly "living" dripstone phenomena died now. According to the maximum temperature values (11 °C) measured in 2012 compared to the data from 1975 (10.4 °C) the temperature rising can be recognized. Because of the proved strong connection with the surface the cause of this temperature rising is the effect of very hot summers of last decades. Unfortunately due to the lack of the long term temperature measurement the potential effect of the global warming can be hardly proved.

### CONCLUSION

Temperature observations were collected inside the Hajnóczy Cave in order to characterize microclimate of a temperate zone cave system in summer condition. The applied wireless sensor system operated well. Cavers affected rapid temperature rises were detected and small scale daily fluctuation was also revealed. Some general characteristics of cave system can be drawn from these observations that concur with existing temperate cave microclimate theory. The first characteristic is that ex-

ternal atmospheric disturbances can affect temperatures of cave system. The daily fluctuation can be observed far from the entrance, which proves new unknown connection of this chamber with the surface. The former air circulation system described on min 1970's by Miklós and Városi was updated according to the measurement carried out in 2012.

The second characteristic is that interior air mass is laminated on bigger chambers of the cave where the natural ventilation does not work. Thirdly it has been recognized that the exterior warm air can reach the upper passages of the cave through the fissures in limestone layer and rises the mean air temperature of the cave (8.5 °C) with 2.5 °C in the Giant chamber.

Therefore the air circulation of the cave system is rather similar to the air circulation of a multi-entrance system. Because of this open system the cave is very sensitive to the effect of the rapid climatic processes and to global climate change in long term.

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